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ADVANCED HIGH TEMPERATURE ENGINE MATERIALS TECHNOLOGY PROGRAM

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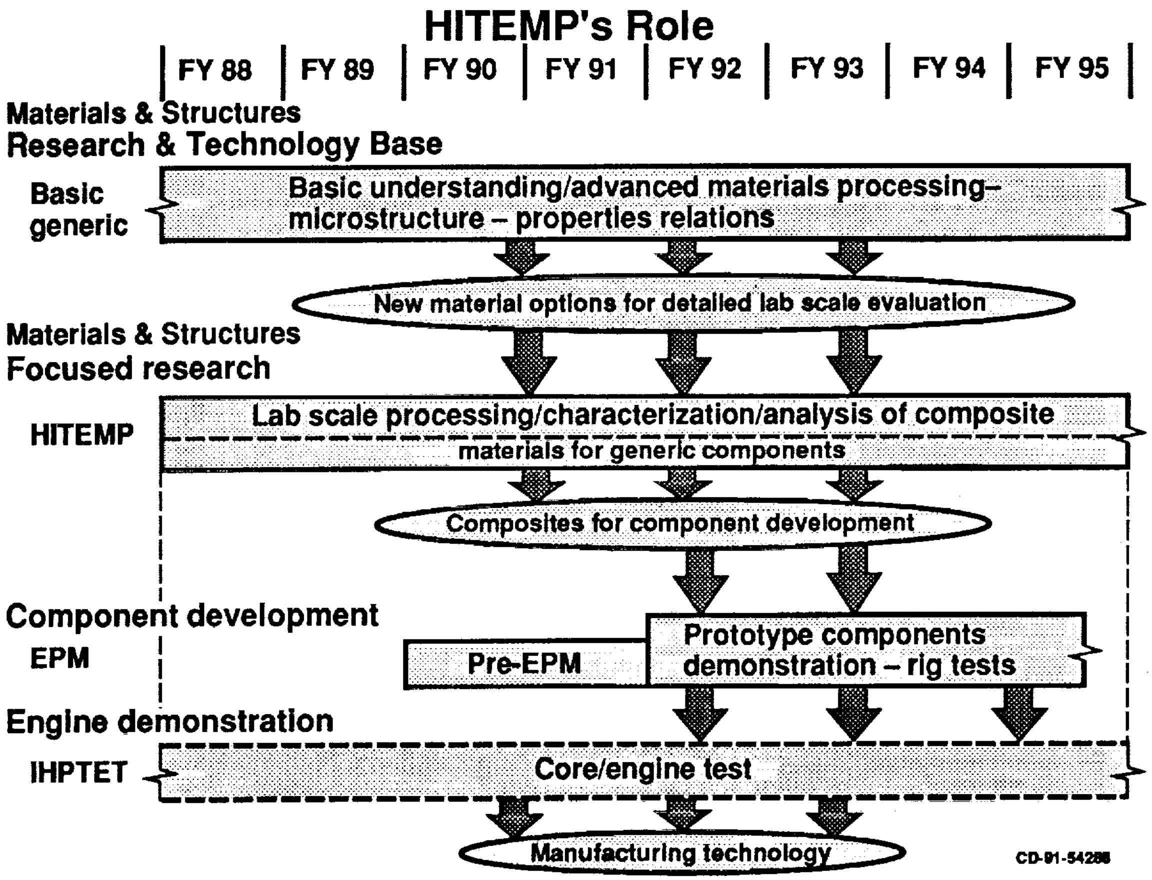
NASA's Advanced High Temperature Engine Materials Technology Program (HITEMP) is directed towards generating the technology for revolutionary advances in structural materials and analysis to enable the development of 21st century civil aeronautics propulsion systems. Major consideration is being given to propulsion systems that will be economical via reducing fuel consumption per passenger mile, reducing direct operating costs, extending life, and improving reliability. To achieve revolutionary advances in propulsion systems for 21st century transports, high temperature materials have been identified as the key technology to be addressed. The HITEMP Program is focusing on lightweight composite materials to gain revolutionary advances in the operating temperatures of advanced engines compared to the current state of the art. Emphasis is being placed on polymer matrix composites (PMC's) for potential use in fans, casings, and engine control systems. Intermetallic/metal matrix composites (IMC's/MMC's) are under investigation for application in such areas as compressor and turbine disks, blades, and vanes, and in the exhaust nozzle. For extremely high temperature applications, ceramic matrix composites (CMC's) are being explored. Initial applications may include liners for the combustor and exhaust nozzle, and turbine vanes and ultimately turbine blades and disks, or blisks.

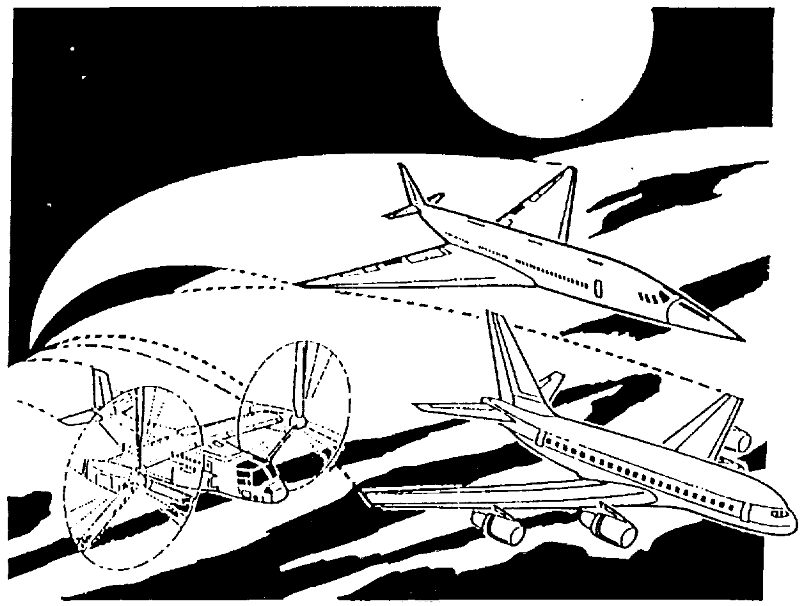
One of the major distinctions between the HITEMP Program, which is focusing on civil transport aircraft propulsion systems, and programs such as the National Aerospace Plane (NASP) and IHPTET is the need for extended high temperature operation at maximum operating temperature. For civil aircraft engines, requirements are in terms of tens of thousands of hours, while for military applications they are in terms of thousands of hours and for NASP, which is a demonstration project, hundreds of hours will meet the goals. As an example of the long term requirement, civil applications, studies on the HSCT engine have indicated that 20 000 hr life with 90 percent at the maximum operating temperature will be required for economic viability. The long term life goal permeates the three classes of composite materials, PMC's, IMC's/MMC's, and CMC's, being investigated in HITEMP.



The objective of the HITEMP program is to generate technology for revolutionary advances in composite materials and structural analysis to enable the development of 21st century civil propulsion systems with greatly increased fuel economy, improved reliability, extended life, and reduced operating costs. NASA considers this program to be a focused research effort that builds upon our basic research programs and that will feed results into application oriented projects such as the proposed NASA new initiative to develop the technology for a 21st century High Speed Civil Transport (HSCT). The Enabling Propulsion Materials (EPM) program is a major effort in the HSCT program and will utilize materials and structures concepts developed in HITEMP as well as elsewhere to provide the gains in engine materials that are required for economic viability and environmental acceptability. Also, HITEMP is closely coordinated with the joint DOD/NASA Integrated High Performance Turbine Engine Technology Program (IHPTET), and new materials from HITEMP may be utilized in future military applications.

Focus

Engines for 21st century transport aircraft



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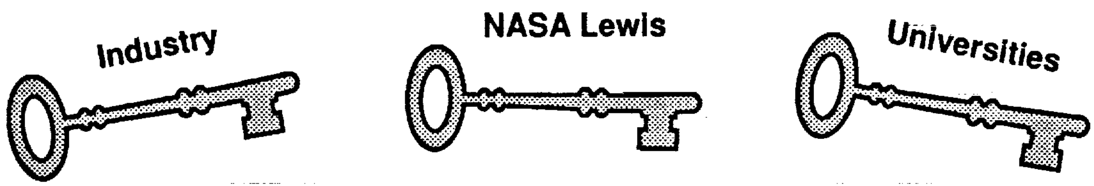
To help guide the research, we are funding preliminary design studies with Pratt & Whitney Aircraft, GE Aircraft Engine Co., and Allison Gas Turbine Division of General Motors. These three companies are studying high speed civil transport engines, ultra-high bypass ratio engines, and rotorcraft engines, respectively.

Cooperation – Key to Success



Industry

- Materials & property requirements for future engine components
- Design codes and validation needed
- Fiber development
- Composite fabrication
- Composite evaluation

NASA Lewis

- Project management
- Fibers/matrices/ composite options: polymers, intermetallics, and ceramics
- Analytical modeling
- Test methods

Universities

- Materials science
- Property characterization
- Structural modeling

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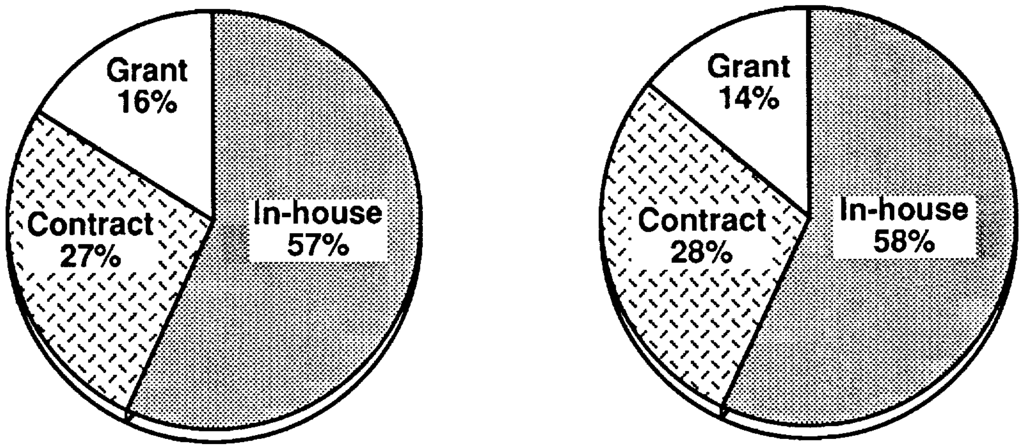
The intent of HITEMP is to combine the skills of NASA Lewis researchers with those from industry and academia to achieve the objective of the program.

Funding Distribution



FY 90 Net R&D funds - $7018K
Total funds - $9216

FY 91 Net R&D funds - $7176K
Total funds - $9776

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Based on FY'90 commitments and projected spending for FY'91, we estimate the distribution of spendable dollars over these 2 years to be about 28 percent in contracts, 15 percent as university grants, and the remainder in-house. A total of 14 contracts have been awarded via the NASA Research Announcement (NRA) route. Two of these have been renewed for a second year. In addition, two other contracts have been awarded by the competitive route, making a total of 16 HITEMP active contracts. An additional five contracts are currently being negotiated. The grant effort within HITEMP is distributed among 12 colleges and universities with some of them having multiple grant programs, for a total of 18 grants.

High Temperature Polymer Matrix Composites

Key issues

- Thermal-oxidative stability
  - Low weight loss
  - Good retention of mechanical properties
- Glass transition temperature
  - Must be at least 25 °C (50 °F) higher than intended upper use temperature
- Processability
- Resin-fiber interactions (interface)
  - Effect on thermal-oxidative stability
  - Effect on mechanical properties
- Oxidation-resistant coatings
- Accelerated aging

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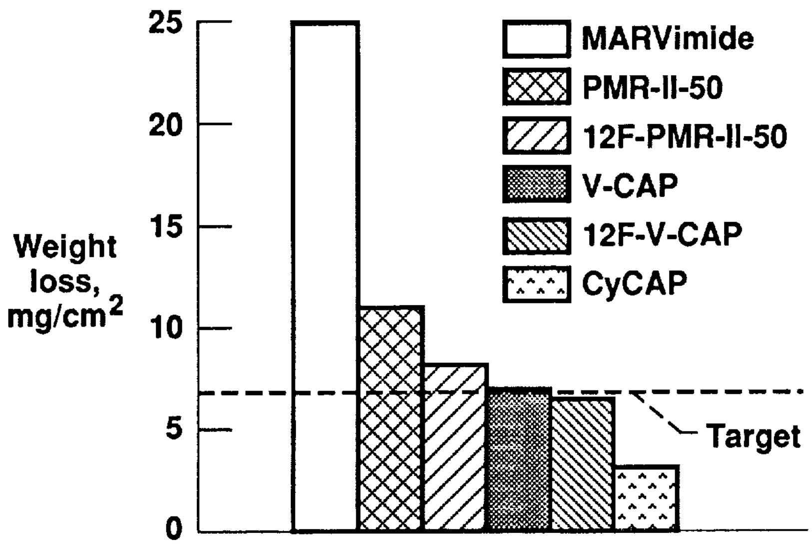
Polymer matrix composites are being developed to achieve a maximum operating temperature of 425 °C (800 °F). Matrices of interest include variations of PMR-II, MARVimide, V-CAP, and CyCAP. Key issues to be addressed in the future are oxidation resistant coatings and the need for conducting accelerated aging tests to determine the time-temperature operating envelope for the PMC's.

Comparison of Neat Resin Weight Losses for Addition Curing Resins

After 500 hr at 345 °C (650 °F), 1 atm Air



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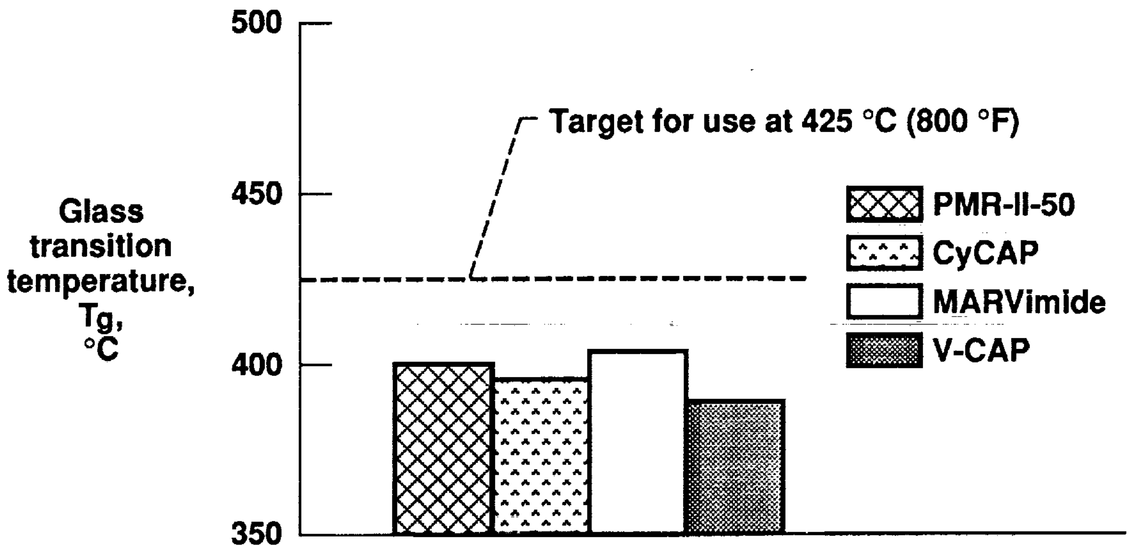
One of the key issues is to achieve thermal oxidative stability, i.e., low weight loss and retention of mechanical properties during the life of a specific component. Short time (500 hr) tests at 345 °C (650 °F) indicate that the CyCAP resin holds the most promise of the resins under investigation.

A Comparison of Glass Transition Temperatures of a Variety of Addition Polyimides



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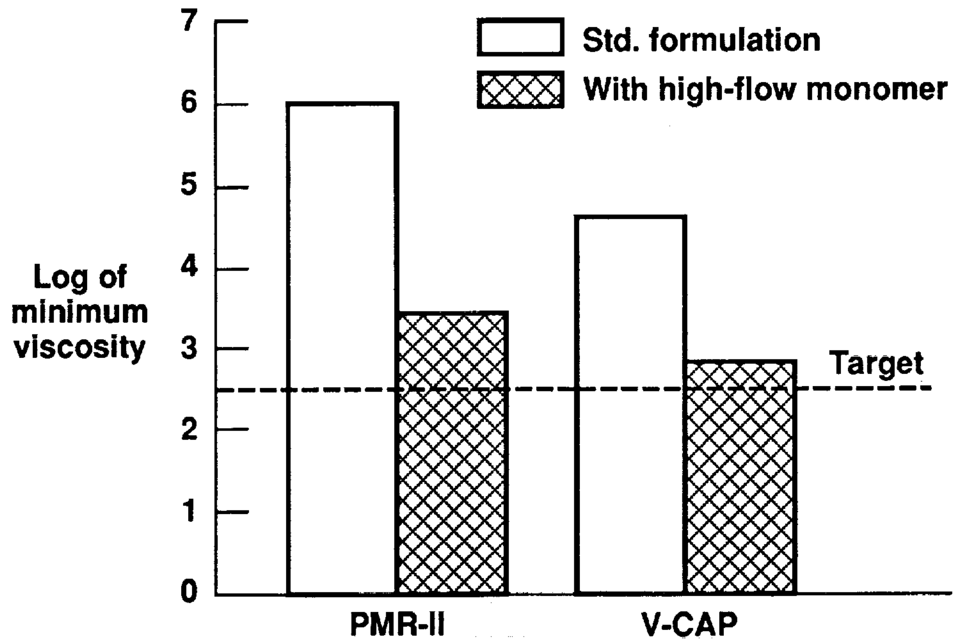
A second critical issue is the processability of the polymer resins. A glass transition temperature of 25 °C (50 °F) above the anticipated use temperature is desirable to maintain mechanical properties. Currently, of the resins studied, there does not appear to be a large variation with composition. On average, the transition temperatures are about 50 °C short of the goal.

Use of High–Flow Monomer Enhances Resin Flow and Improves Processability



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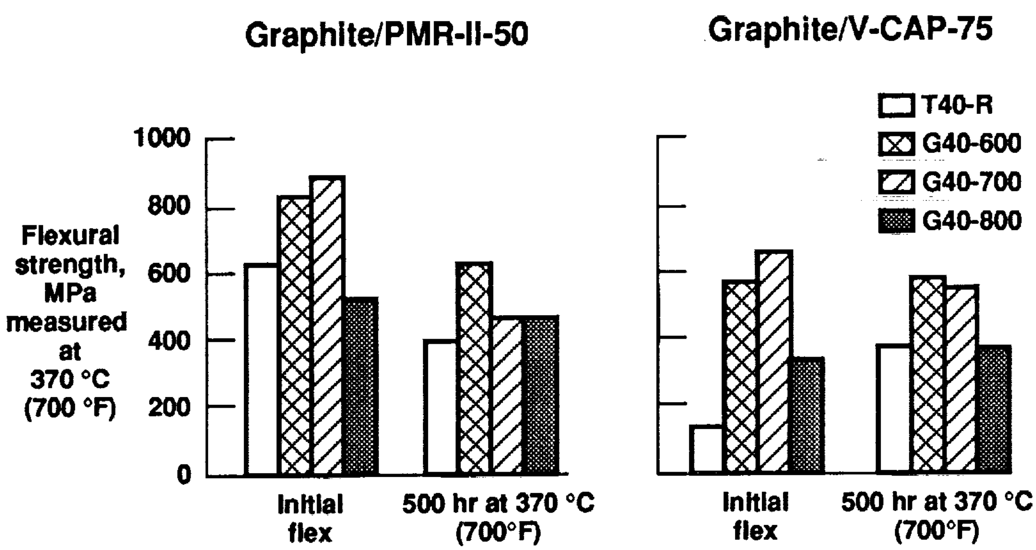
A second factor to be considered in processability is the resin's capability to flow as determined by viscosity measurements. A high flow monomer has been added to PMR-II and to V-CAP with successful results. In both cases a substantial reduction in viscosity was produced which will allow for more complete removal of volatile byproducts formed during curing. A final key issue under investigation is that of fiber-resin interaction during service. Depending upon the interface reaction, both thermal-oxidative stability and mechanical properties may be degraded.

Choice of Graphite Fiber Greatly Influences the High Temperature Performance of PMC's



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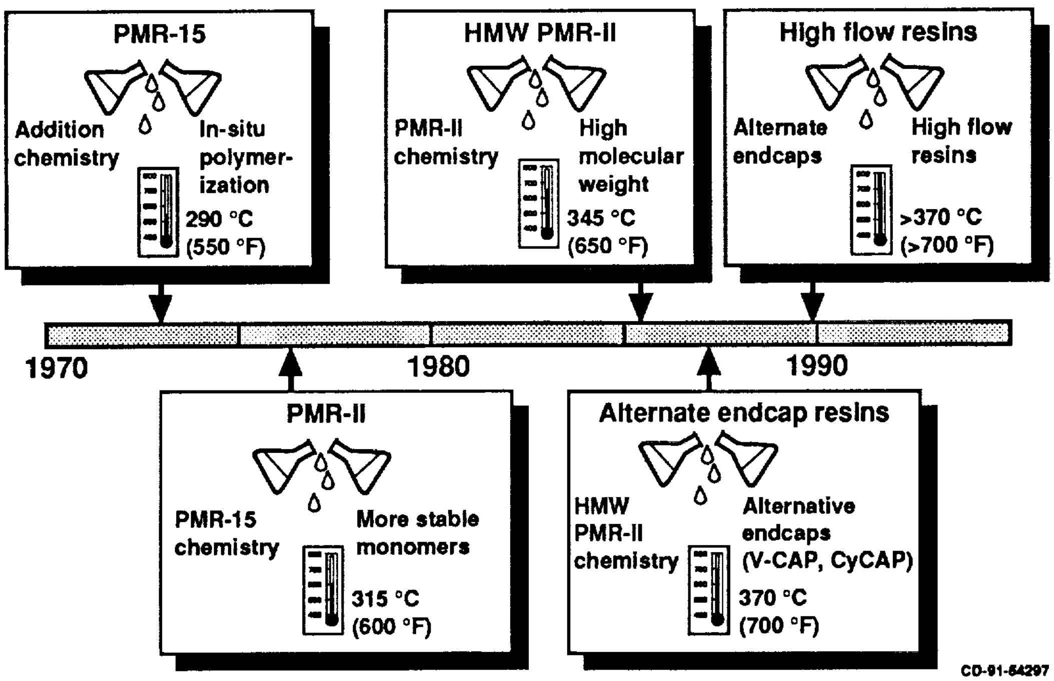
Results have shown that choice of graphite fiber for a specific matrix composition can greatly impact the strength of PMC's after high temperature exposure. PMR-II-50 and V-CAP-75 with the G40-600 fiber exhibited the highest flexural strength after exposure at 370 °C (700 °F) compared to the use of T40-R, G40-700, and G40-800 fibers.

Two Decades of High Temperature Polymer Research at NASA Lewis



From the introduction of PMR-15 in the early 1970's to the present, PMC research at NASA Lewis has demonstrated an increase in use temperature from 290 °C (550 °F) to 370 °C (700 °F) for the advanced composites such as the high molecular weight PMR's and alternate endcaps such as V-CAP and CyCAP.

High Temperature Polymer Matrix Composites

Future research directions

- Use of high flow systems to maximize prepolymer molecular weight
- Use of more stable endcaps to improve thermal-oxidative stability
- Nitrogen postcuring to get high T_g's necessary for 425 °C (800 °F) goal
- Potential use of high temperature resins as fiber sizings

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The use of high flow systems to maximize prepolymer molecular weight is viewed as the next fruitful area of research where use temperature may be further increased. Other future areas of research will emphasize nitrogen postcuring to achieve the desired glass transition temperature and along with coatings, in turn, achieve long term durability at an operating temperature of 425 °C (800 °F).

Intermetallic Matrix Composites

Key issues

- CTE mismatch
- Oxidation resistance
- Composite modeling/architecture

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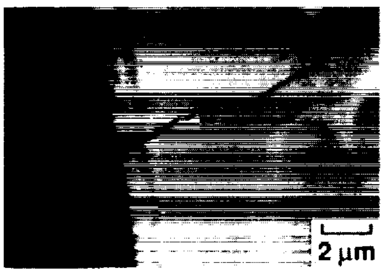
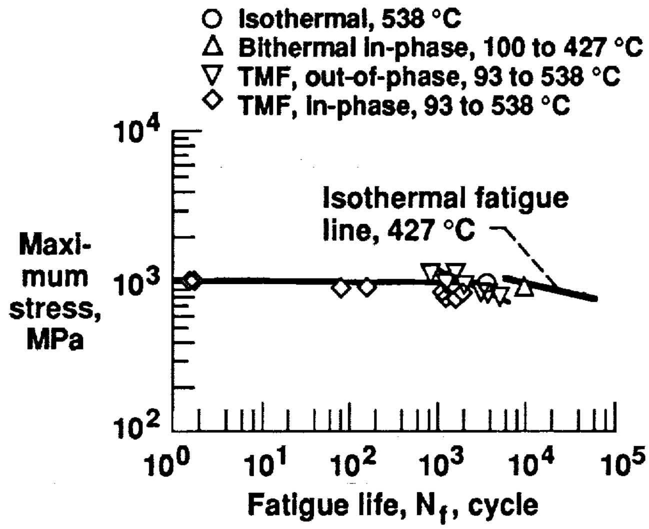
Metal/intermetallic matrix composites under investigation in HITEMP are slated for use temperatures that bridge the gap between PMC's and CMC's, or above 425 °C (800 °F) to about 1315 °C (2400 °F). Intermetallic compounds, especially the aluminides, provide a low density matrix and the potential for good oxidation resistance at the anticipated use temperatures. However, the aluminides have coefficients of thermal expansion (CTE's), ranging from about 10×10^{-6}/°C for Ti_3Al to 23×10^{-6}/°C for FeAl. Since the primary fiber currently available, SiC SCS-6, has a relatively low coefficient of thermal expansion (5×10^{-6})/°C), the issue of fiber-matrix CTE mismatch is the key issue for IMC's.

Effects of CTE Mismatch

Growth of radial cracks in SiC/Ti_3Al due to 1000 thermal cycles between 85 and 815 °C



Thermomechanical fatigue life results for $[0]_9$ SiC /Ti-15-3-3-3



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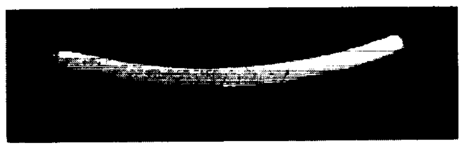
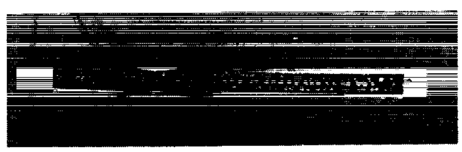
The detrimental effect of CTE mismatch is evidenced during both thermal cycling and thermomechanical fatigue (TMF) testing. For example, pre-existing radial cracks in SiC/Ti_3Al propagated into the matrix during thermal cycling in vacuum between 85° and 815 °C. In TMF testing cyclic lives were greatly reduced from those obtained in isothermal fatigue tests at both 427 and 538 °C. For in-phase TMF tests cyclic lives were reduced several orders of magnitude relative to out-of-phase TMF tests.

Experiments/Modeling to Understand CTE Mismatch

Thermally cycled FeAl and FeCrAlY composites

Composite system	23° to 825 °C, 1000 cycles (rate = 25 °C/s)	$\frac{\text{CTE matrix}}{\text{CTE fiber}}$, 10^6/°C
FeAl/W		$\frac{23}{5} = 4.6$
FeCrAlY/W		$\frac{14}{5} = 2.8$
FeCrAlY/Al_2O_3		$\frac{14}{9} = 1.6$

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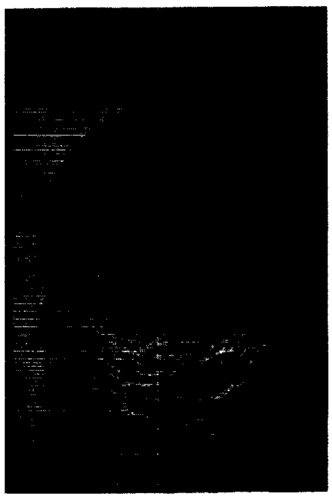
This problem manifests itself in thermal cycling where strength decreases and in thermal mechanical fatigue where life is degraded compared to isothermal tests. The severity of the problem is indicated by comparison of the degree of permanent deformation of composites with varying matrix-fiber CTE ratios. From these limited data, it appears that a ratio of 1.6 may be acceptable without severe degradation of the composite.

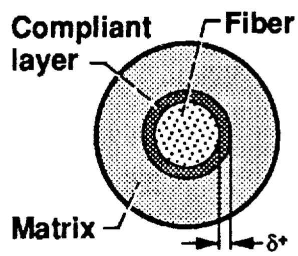
Concepts to Resolve CTE Mismatch

High CTE fibers



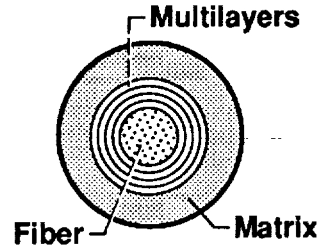
Sputtered Nb_2Be_{17} fiber

Compliant layer



- Joint effort with Textron Specialty Materials
- In-house & UCSB analytical modeling (concentric cylinder model, F.E.M.)
  - Thermal elastic
  - Thermoelastic-plastic
  - Shakedown

Graded or multilayer



- Joint effort with Textron Lycoming-Sarnoff
- Multilayer analysis, concentric cylinder model to be studied

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A threefold approach is underway to overcome the CTE issue in IMC's, including identification of high CTE fibers, application of a compliant layer, and the use of a graded interface of multiple layers at the interface.

Oxidation Resistance

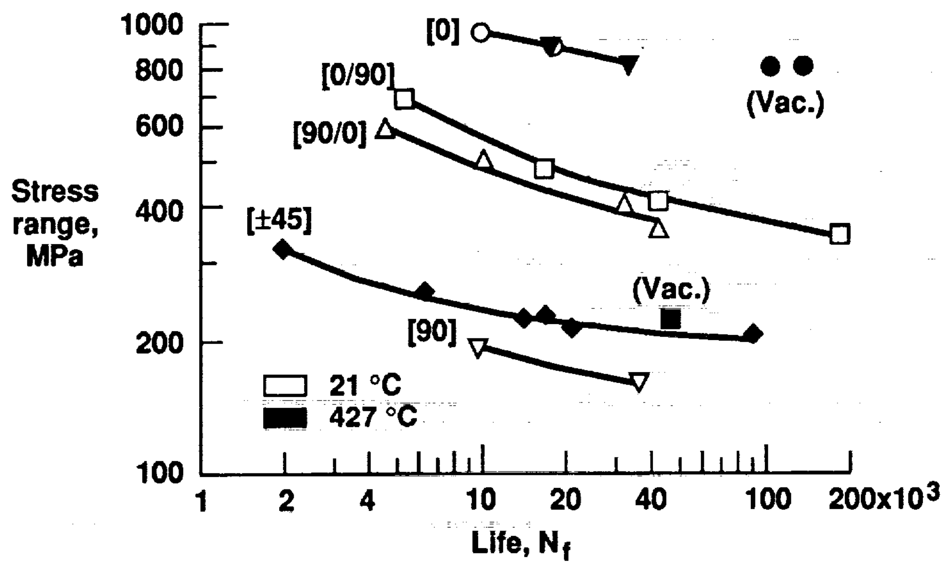
Ti_3Al + Nb	FeAl
• Pack aluminide ($TiAl_3$) coatings provide excellent protection on matrix material, but fail on composites. • Ductile plasma sprayed NiCrAlY coatings are being studied.	• Oxidation resistance is adequate for intended use temperature of 1000 °C. • Zr-, B-, and Hf-doped alloys are being characterized to 1100 °C.

NiAl	$NbAl_3$
• Zr-doped NiAl alloys must have more than 40 at.% Al for good oxidation properties to 1200 °C. • Diffusion-based life prediction model is being developed.	• Patented alloy (Nb-40Al-8Cr-1W-1Y) has oxidation resistance at 1200 °C comparable to Al_2O_3-forming Ni-base alloys. • AlNbCr is an identified phase that provides oxidation resistance. • Yttrium is essential for optimum behavior.

CD-91-54303

Another key issue for IMC's is the limiting oxidation use temperature of the matrices. Cyclic oxidation behavior of the primary matrices being investigated in HITEMP have been characterized, models developed to predict their behavior, and their oxidation limiting use temperatures defined. Current emphasis is on coatings to further extend the life of these matrices and the composites.

Isothermal Fatigue Life Curves for Various Architectures of 35 vol% SiC/Ti–15–3 Composite



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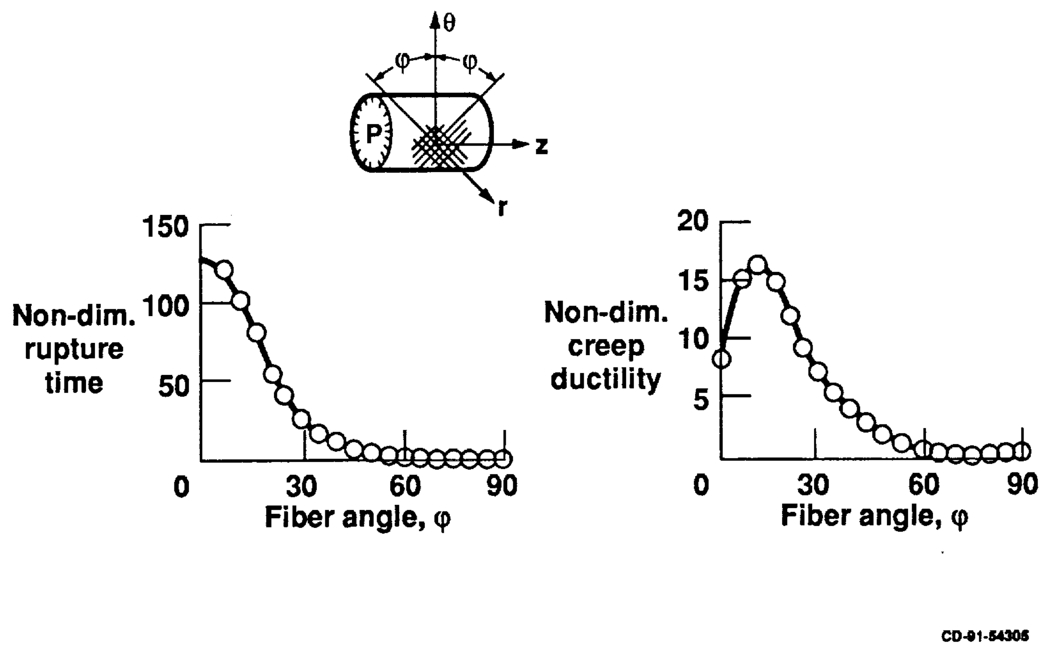
At the lamina level, isothermal fatigue life curves have been experimentally determined for SiC/Ti-15-3 which will be used in verifying analytical models and defining fiber architectures for specific applications. Per given stress range, the $[0]_8$ specimens have the longest life, followed by the $[0/90]_{2S}$, the $[90/0]_{2S}$, the $[\pm 45]_{2S}$, and the $[90]_8$ orientations, respectively. For the few specimens tested, no difference in the fatigue life was observed between the $[0]_8$ specimens tested at 427 °C or those tested at room temperature.

Creep and Creep Rupture of MMC's: Rings



Designers want long life and high creep damage tolerance (ductility) in MMC structures (e.g., rings). A recent creep/creep-rupture model for MMC's serves to achieve optimal fiber configurations in creep limited structures.

Intermetallic Matrix Composites

Future research directions

- Continue effort to identify and fabricate high CTE fibers.
- Experimentally verify analytical models for compensating coatings to overcome CTE mismatch.
- Develop fiber coatings for either reaction prevention or bonding enhancement.
- Improve ductility/toughness of matrix candidates through ductile wire toughening concepts.
- Develop reliable oxidation resistant coatings.
- Develop composite models to predict deformation and service life.

CD-91-54306

The issue of fiber-matrix CTE mismatch will continue to plague IMC's until fiber and/or fiber-coating systems are developed that minimize the mismatch to a permissible limit. Coatings may also be required to optimize the fiber-matrix bond. Ductility/toughness of the matrix is another key issue being approached by analytical modeling and experimentally via microalloying, macroalloying, and ductile second phase toughening.

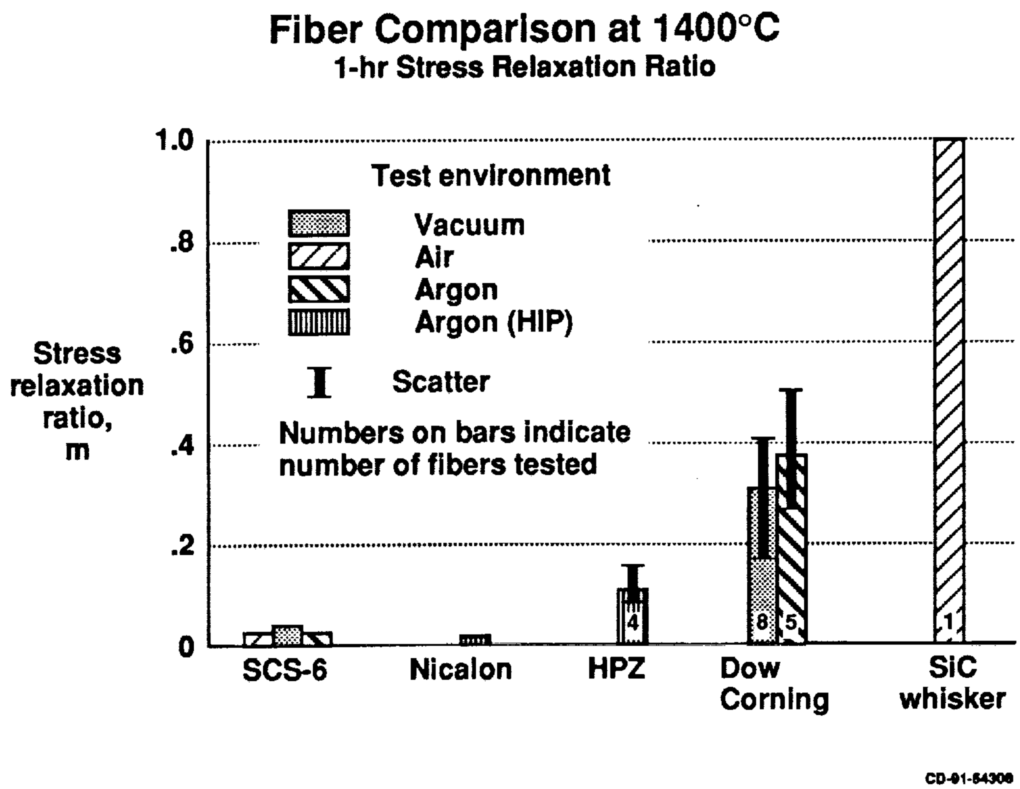
Ceramic Matrix Composites

Key issues

- Strong, small diameter fibers with thermal stability and creep resistance above 1400 °C
- Weak fiber/matrix interfaces with thermo-oxidative stability
- Oxidation resistance matrices with high fracture strength
- Identification of deformation and damage mechanisms and accurate modeling for reliable CMC structures
- Test methodologies for evaluating CMC structural and environmental performance at high temperature

CD-91-54307

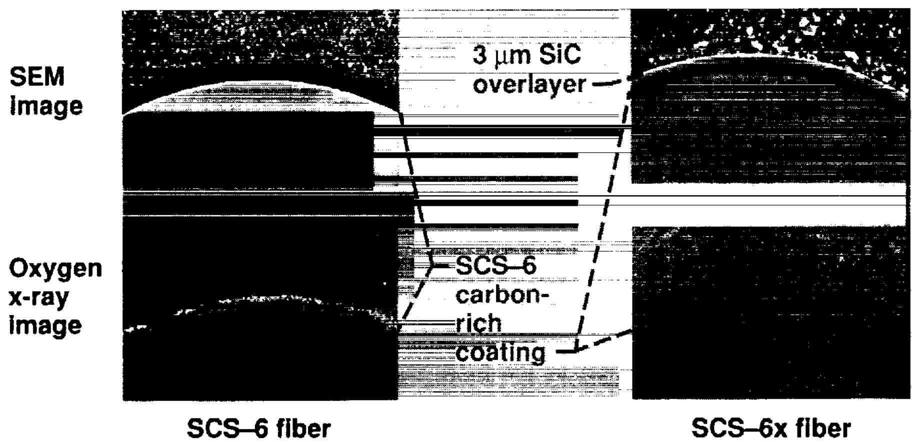
Structural ceramic matrix composites are being explored to provide revolutionary advances in the maximum operating temperature of gas turbine engines. A critical issue for these materials is to develop a high strength, small diameter fiber with thermal stability and creep resistance over the temperature range of 1300 to 1650 °C (2375 to 3000 °F).



A simple measure of creep resistance via a bend test at 1400 °C (2550 °F) has provided a ranking of the creep strength of several fibers. For this bend test, the stress relaxation ratio (as-received/after 1400 °C heat treatment) decreases from unity as the fiber creeps. The most creep resistant fibers evaluated to date are single crystal silicon carbide whiskers. For polycrystalline fibers, creep resistance improves with freedom from silicon and oxygen and with increasing grain size. However, larger grained fibers also display lower tensile strengths.

New Coating for SCS–6 Fibers Improves Oxidative Stability

Interface in SCS–6/RBSN composites after 100 hr, 600 °C in air



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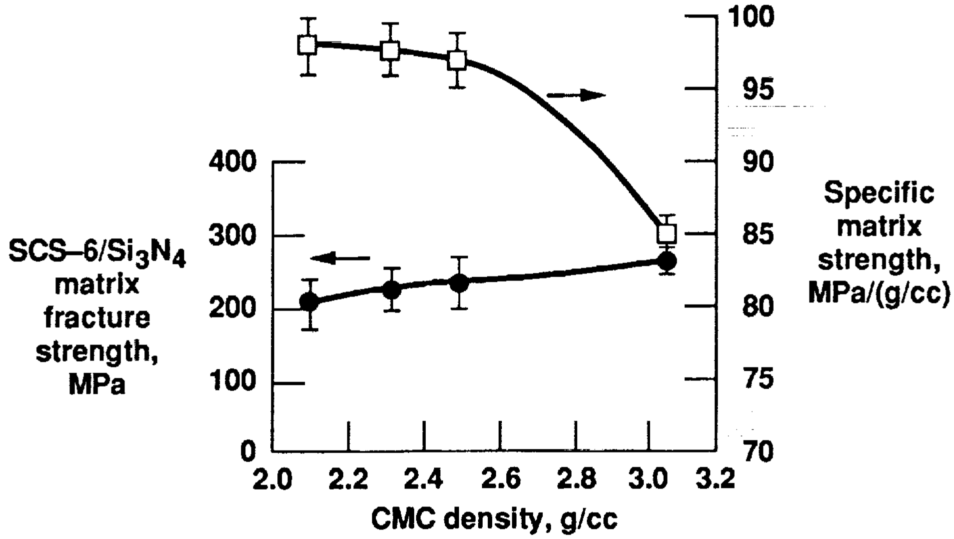
A second key issue with CMC's is the fiber-matrix interface, where a weak, thermo-oxidative resistant interface is desirable. Textron has recently developed an SiC overlayer approach which significantly reduces oxygen attack of the SCS-6 fiber. This new fiber, SCS-6x, has the potential for use in porous/cracked matrices as well as in matrices with carbon-attacking compositions, such as oxides, metals, and intermetallics.

Porous Matrix CMC Can Display Better Specific Strength Than Dense Matrix CMC



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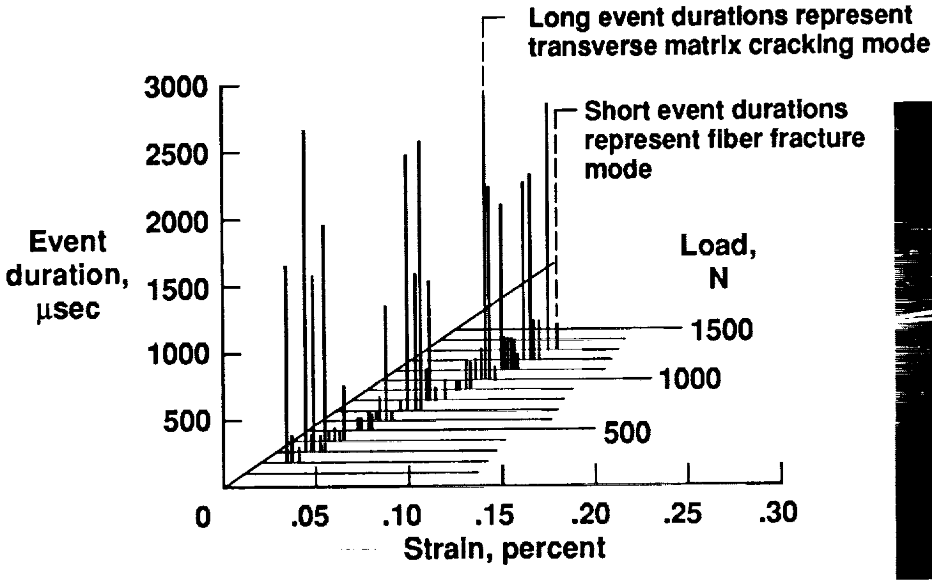
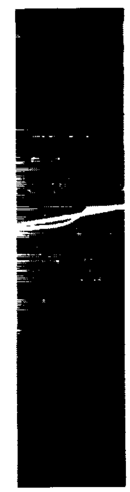
Matrix fracture strength is a critical issue for the use of CMC's in gas turbine engine applications. Although the strength of SiC SCS-6/RBSN shows a slight increase with increasing density of the composite, on a specific strength basis the low density, porous material exhibits superior strength. This implies that the need for high density CMC's may be reduced and widens the fabrication opportunities for high strength composites.

Damage Accumulation and Failure Mechanisms in SiC/RBSN





X-radiography results at failure

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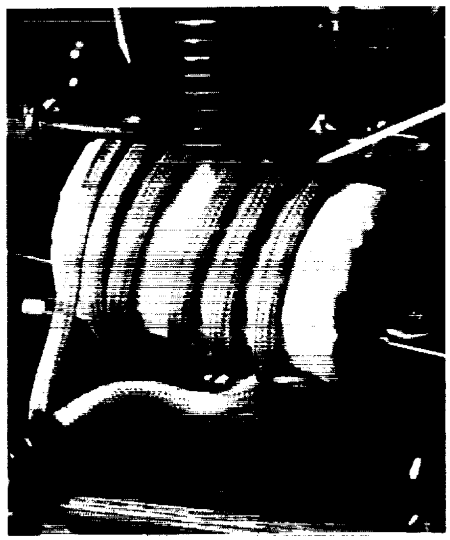
Identification of deformation and damage mechanisms is a critical issue in the development of modes to predict the life of CMC's. Acoustic Emission (AE) has been used in conjunction with x-radiography to detect both matrix and fiber cracking of SiC/RBSN composites tested in tension. The AE results have been confirmed by radiography conducted at different load levels.

Susceptor Design Used with a 5-kW Induction Heater for Testing CMC's to 1650 °C (3000 °F)



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The proposed extreme use temperatures of CMC's require the development of high temperature laboratory test equipment that will permit accurate characterization of these materials. Test apparatus has been developed that will permit testing of CMC's in tension and fatigue up to 1650 °C (3000 °F).

Ceramic Matrix Composites

Future research directions

- Define thermomechanical performance limits for polycrystalline and single crystal SiC fibers and single crystal alumina fibers.
- Explore compositions and processing approaches for
  - Improved single crystal oxide fibers
  - Stable CMC interfaces
  - High thermal conductivity Si-based CMC.
- Demonstrate environmental and structural durability limits for high potential CMC.
- Test methodologies for evaluating CMC structural and environmental performance at high temperature.

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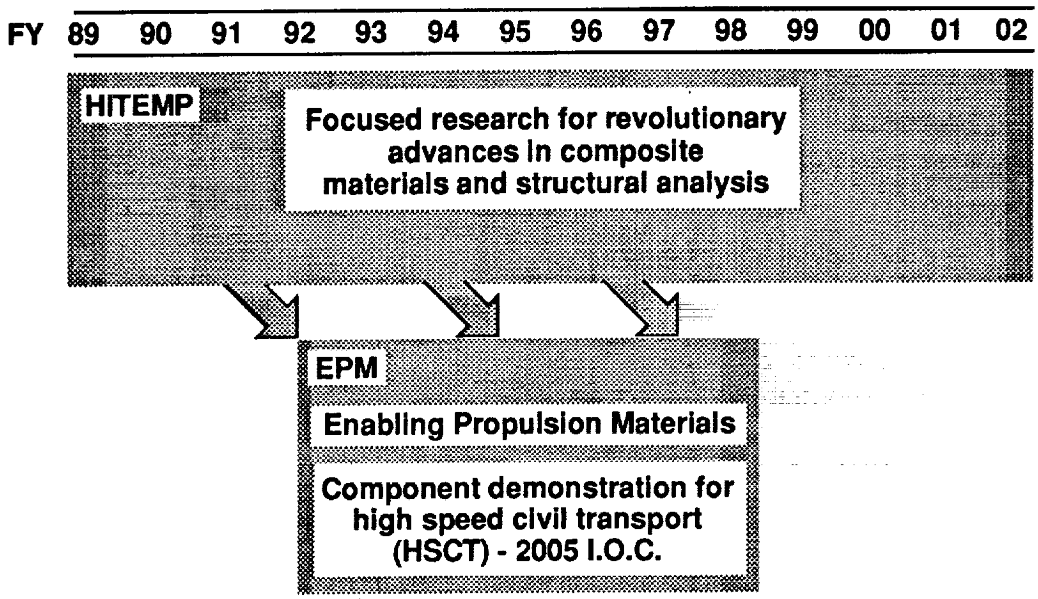
To extend the potential use temperature of CMC's, future research will continue to focus on the development of SiC and Al_2O_3 fibers. Other areas of research will focus on stable interfaces, high thermal conductivity Si-based CMC's, and demonstration of the environmental and structural durability of the most promising materials.

Concluding Remarks
HITEMP future research directions



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Transfer of the technology generated in HITEMP hopefully will see fruition in programs such as IHPTET and in the new Enabling Propulsion Materials (EPM) Program. The major areas of emphasis in the EPM Program for the high speed civil transport will be the combustor liner which will require the application of CMC's to minimize NO_x and the exhaust nozzle where IMC's will be required because of their high strength-to-weight ratio potential.